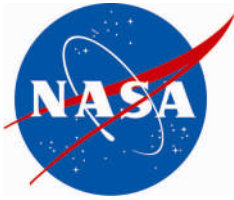


NASA/TM-2008-215104  
NESC-RP-07-20/06-049-E



# Feasibility of Conducting J-2X Engine Testing at the Glenn Research Center Plum Brook Station B-2 Facility

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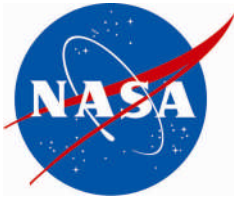
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January 2008


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# **Feasibility of Conducting J-2X Engine Testing at the Glenn Research Center (GRC) Plum Brook Station (PBS) B-2 Facility**


**March 15, 2007**

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## Report Approval and Revision History

Approved: _____	Original signed on file _____ NESC Director	3-20-07 _____ Date
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Revision	Description of Revision	Author	Effective Date
Base	Initial Release	Mr. Armis L. (Len) Worlund, Propulsion Consultant (NASA Ret)	03/15/07

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## **Volume I: Technical Assessment**

### **1.0 Notification and Authorization**


The request to conduct an assessment on the J-2X engine testing was submitted to the NASA Engineering and Safety Center (NESC) on August 3, 2006.

The authority to proceed was approved in an out-of-board action on August 31, 2006. Mr. Armis L. (Len) Worlund, Propulsion Consultant (NASA Retired) was requested to lead the assessment. The Assessment Plan was approved by the NESC Review Board (NRB) on October 12, 2006.

The final report and outbrief was presented to the NRB on March 15, 2007.

Key stakeholders for this assessment are Mr. Kevin Power, Stennis Space Center (SSC) Propulsion Test Integration Group (PTIG), Constellation Program (CxP) Test and Evaluation Office at Johnson Space Center (JSC), Exploration Launch Office (Crew Launch Vehicle (CLV)), Rocket Propulsion Test (RPT) Program and Mr. Michael Kynard, J-2X Project Management.



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## 2.0 Signature Page


\_\_\_\_\_  
Mr. Armis L. Worlund                      Date  
NESC Lead

\_\_\_\_\_  
Mr. James R. Brown                      Date  
Consultant-P & W, Retired

\_\_\_\_\_  
Mr. William G. Hooper                      Date  
Consultant-Aerojet-Retired


\_\_\_\_\_  
Mr. Jan C. Monk                      Date  
Consultant-NASA, Retired

\_\_\_\_\_  
Mr. Thomas W. Winstead                      Date  
Consultant-NASA, Retired

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### 3.0 Team List

<b>Name</b>	<b>Position/Technical Discipline Affiliation</b>	<b>Center/Contractor</b>
<b>Core Team</b>		
Armis L. Worlund	Lead	Consultant- Lee & Associates
James R. Brown	Engine Development and Performance	Consultant- Lee & Associates
Jan C. Monk	Engine Systems Evaluation and Tests	Consultant- Lee & Associates
Thomas W. Winstead	Vehicle Integration and Verification	Consultant- Lee & Associates
William G. Hooper	Propulsion/Facility Development & Operation	Consultant- Lee & Associates
<b>Advisors and Observers</b>		
Kevin Power	Advisor	SSC PTIG
James Ryan	SSC Liaison	SSC NESC
Ron Cull	Advisor	Rocket Propulsion Test Management Board (RPTMB)
Derrick Cheston	Advisor	NESC Chief Engineer GRC
Charles Schafer	Advisor	NESC Chief Engineer MSFC
Kerry Remp	Advisor	S&MA GRC

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## 4.0 Executive Summary

A trade study of the feasibility of conducting J-2X testing in the Glenn Research Center (GRC) Plum Brook Station (PBS) B-2 facility was initiated in May 2006 with results available in October 2006. The Propulsion Test Integration Group (PTIG) led the study with support from Marshall Space Flight Center (MSFC) and Jacobs Sverdrup Engineering. The primary focus of the trade study was on facility design concepts and their capability to satisfy the J-2X altitude simulation test requirements. An aerial view of the overall PBS B-2 facility is shown in Figure 4.0-1.



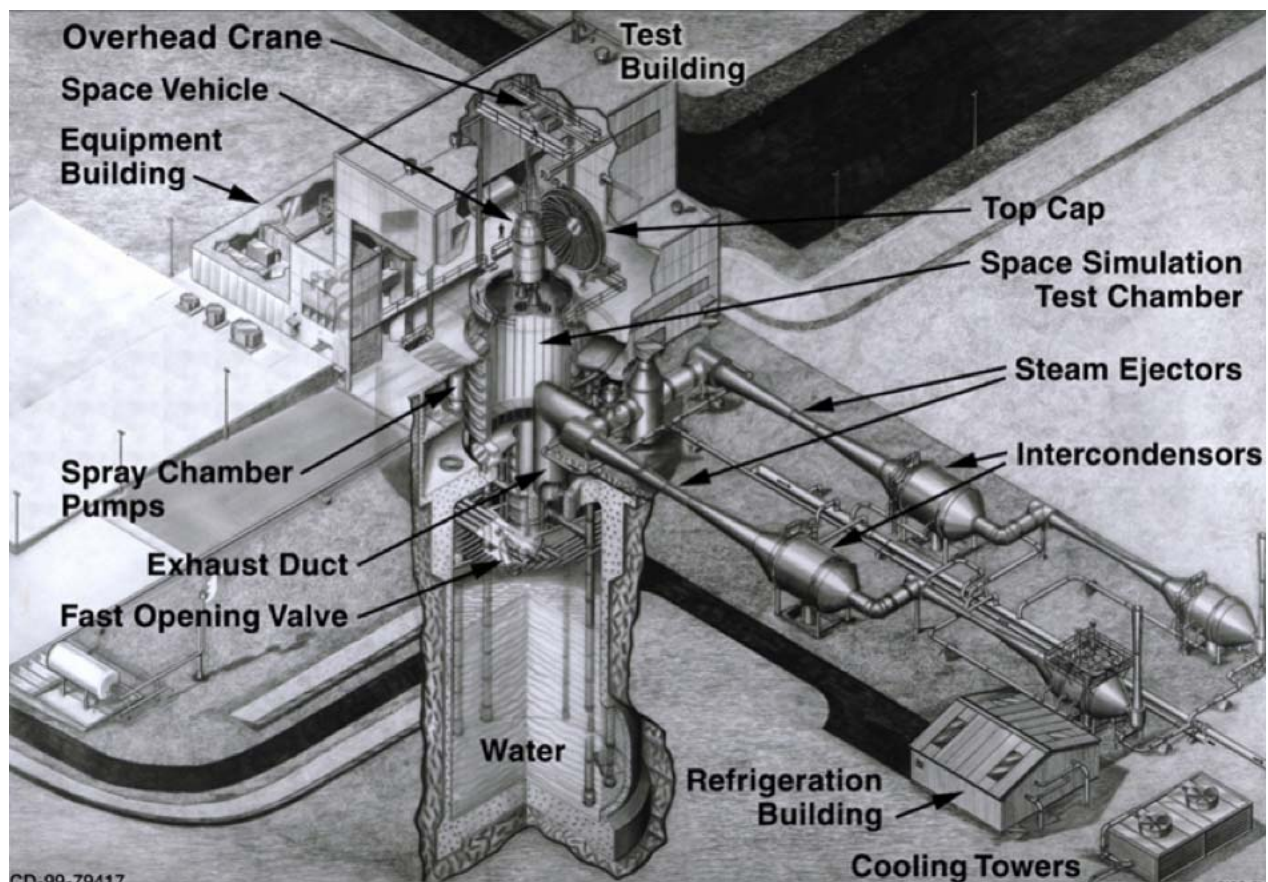
**Figure 4.0-1. GRC PBS B-2 Facility Aerial View**

An Independent Review Team (IRT) composed of consultants with extensive experience in the aerospace industry and Government evaluated the trade study results and provided recommendations to increase the probability of meeting the test objectives. The IRT's

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assessments included trade study documentation, facility requirements document (FRD), J-2X test objectives and development plans, and technical discussion/briefings by GRC and Jacobs Sverdrup Engineering personnel.

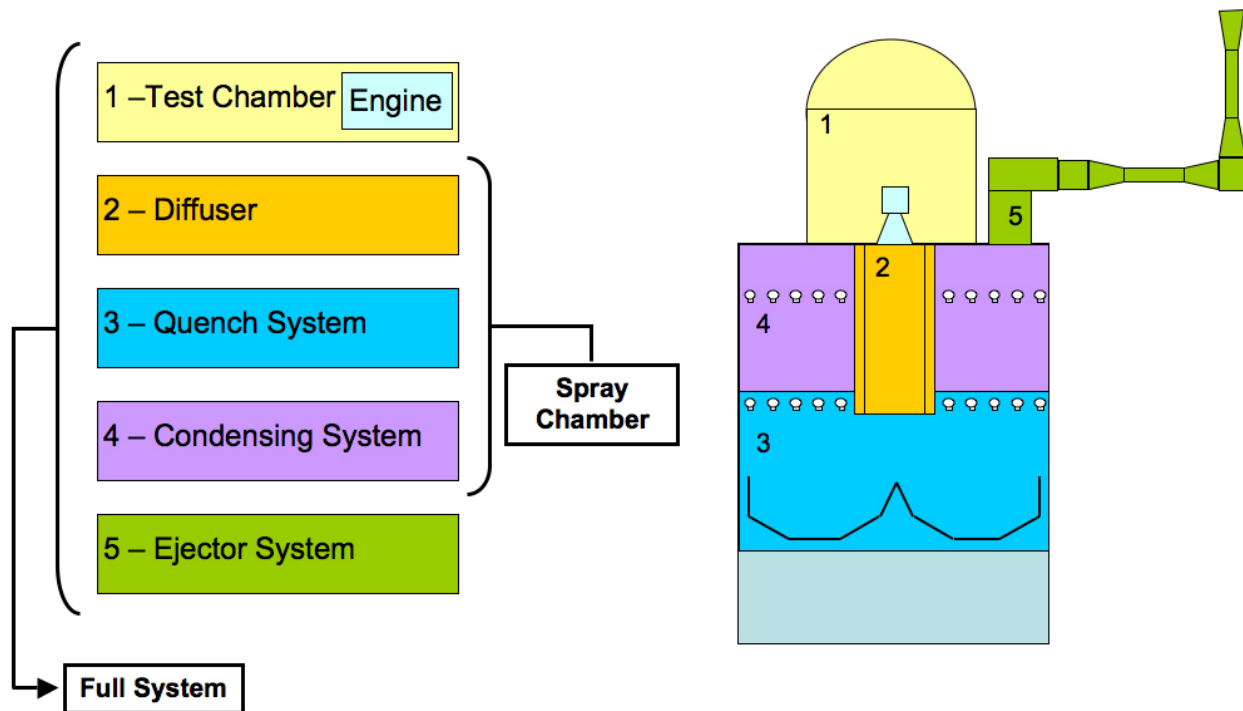
The propulsion systems tested in the B-2 facility were in the 30,000-pound (30K) thrust class. The J-2X thrust is approximately 10 times larger. Therefore, concepts significantly different from the current configuration are necessary for the diffuser, spray chamber subsystems, and cooling water. A cross-sectional view of the PBS B-2 facility is shown in Figure 4.0-2. A sketch illustrating the terminology used in this report is provided in Figure 4.0-3.



**Figure 4.0-2. Cross-Sectional View of the PBS B-2 Facility**



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**Figure 4.0-3. PBS B-2 Facility Terminology**

Steam exhaust condensation in the spray chamber is judged to be the key risk consideration relative to acceptable spray chamber pressure. Further assessment via computational fluid dynamics (CFD) and other simulation capabilities (e.g. methodology for anchoring predictions with actual test data and subscale testing to support investigation of steam cooling process) are required.

Recommendations related to further evaluation include:

- If the studies in modeling do not yield a high level of confidence that the spray chamber pressure can be held low enough to maintain diffuser operation, then an evaluation will be needed to determine the need for an additional spray chamber before the main ejectors and/or an increase in ejector capability.
- Assessment of the exhaust flow conditions from the spray chamber is that the 12-foot diameter outlet may be a significant restriction and additional assessment is required to achieve flow rates capable of maintaining target chamber pressures.
- As a subscale test is defined, considerations should include non-condensable hydrogen and scaling as a pie segment of the B-2 chamber.

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- d) J-2 X element out year planning should evaluate options to maintain a program schedule if spray chamber pressure exceeds design value, or modification to the spray chamber is required during activation to meet design value.

The primary test chamber issues are the configuration of propellant system and access for engine inspection. Propellant delivery systems recommendations include:

- a) Run tanks in or near to the test cell.
- b) Similarity to flight vehicle propellant feed system (or to the Stennis Space Center (SSC) sea level test facility) to preclude introduction of the test facility specific effects such as engine start transient anomalies.


Inadequate access to the engine from below for inspection and maintenance/repair can impact test turn around schedule. Vertical access requirements are not defined in the FRD. Therefore, it is recommended to define facility concepts to provide access and to evaluate impact on other subsystems. Vertical access requirement of 6 feet between the nozzle exit and the floor should be used until the FRD requirement is added.

Currently, the FRD is not aligned with the J-2X test objectives, and this needs to be addressed.

The J-2X restart testing does not directly address the Constellation Program (CxP) Earth Departure Stage (EDS) restart requirements.

Recommendations relative to EDS/J-2X restart are:

- a) Revisit the requirements for Hot and Cold Soak Tests to determine their benefit versus deferring until the EDS stage or simulated stage is available.
- b) FRD for EDS should be initially based on historical data (S-IVB, Centaur, Delta III, Delta IV, etc.). Vehicle and J-2X element offices should evaluate the impact of the nozzle extension on restart of the EDS. There is precedence in the Delta III/Delta IV development in that the nozzle extension was not installed for restart tests.
- c) Because the EDS testing will probably require a Test Chamber height increase, a cost/benefit trade study should be conducted to determine effectiveness of significantly increasing the test chamber height. Also, evaluate raising the facility subsystems in the test chamber if driving requirements change with the focus on accommodating EDS with minimum changes to the Thrust Takeout Structure (TTOS).

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## 5.0 Assessment Plan

The plan for the non-advocate review of the feasibility was to use an IRT of nationally-recognized Government and Industry consultants. The IRT have broad knowledge and expertise in the development, validation, and operation of liquid propulsion engines and systems for space launch vehicles. Also, IRT members have experience in testing and evaluation of space engines in altitude simulation facilities.


The review under the auspices of the NESC was in support of future NASA Exploration efforts. The activities of the IRT were performed in accordance with the applicable NESC procedures and processes.

The IRT conducted a review of the facility design trade study to conduct J-2X thermal vacuum/hot-fire engine testing at the GRC PBS and have made recommendations that would increase the probability of meeting the J-2X engine test objectives for altitude simulation testing.

The IRT familiarization was based on two briefing packages. One was the preliminary report results briefing of the "Facility Design Trade Study to Conduct J-2X Thermal Vacuum Hot-Fire Engine Testing at Plum Brook Station" dated 15 August 2006. The other was the "GRC PBS Facility Study Finding" dated 12 October 2006. The IRT developed questions that were used to focus subsequent discussions with the Facility Trade Study Team personnel. The IRT completed an on-site visit of the PBS B-2 facility. The site visit focused on the modifications required to restore thermal vacuum test capability to PBS and the upgrades being defined to conduct J-2X engine testing in the B-2 facility. During the visit, the IRT was briefed by GRC/PBS and SSC personnel on the status of their activities. The SSC briefing included some impacts of the revised requirements for the B-2 Trade Study that were implemented subsequent to 15 August 2006. The SSC contractor updated the evaluation to include the impact of reducing the test chamber pressure to 0.16 pounds per square inch absolute (psia). The GRC/PBS studies were continuing based on a test chamber pressure of 0.40 psia.

The GRC/PBS in-house results developed in support of the B-2 Facility Trade Study were provided in response to a request by the IRT. GRC also provided a copy of the Aero Systems Engineering (ASE) document referenced in the trade study. A partial draft of the B-2 trade study report and briefings, provided on 22 November 2006, was reviewed. Soon after, updated draft reports were provided on 22 December 2006 and on 19 January 2007. The IRT reviewed historical altitude simulation test programs and facilities relative to the B-2 Trade Study Results.

The J-2X test objectives, development plan, and FRD for altitude simulation testing were evaluated relative to the B-2 Trade Study. A Technical Interchange Meeting (TIM) was held

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with Jacobs Sverdrup Engineering and GRC/PBS personnel that focused on diffuser concepts and heat and mass transfer dynamics in the spray chamber.

The IRT did not provide any detailed engineering analyses. However, the team conducted cursory analysis to assess the sensitivity of steam condensation in the spray chamber.

The IRT provided observations and recommendations that should lead to better achievement of the J-2X test objectives for altitude simulation testing.

## 6.0 Observations and Recommendations

The B-2 feasibility study was based on a set of requirements provided to the study team and was used to define the facility concept as documented in the *Facility Design Trade Study to Conduct J-2X Thermal Vacuum Testing at the Glenn Research Center Plum Brook Station B-2 Facility Final Report, draft*, dated 19 December 2006. Additional information was derived from Pratt & Whitney Rocketdyne (PWR) FRD, J-2X test objectives, and development plans. Technical discussions and briefings by GRC and Jacobs Sverdrup Engineering personnel were invaluable.

The IRT's observations and recommendations related to the PBS conceptual facility are discussed in the following subsections with the observations in each section listed in order of critically based on the team's assessment. The observations and recommendations are presented categorically as Requirements (R), Integration (I), Test Cell (TC), Spray Chamber (SC), Ejector System (ES), Propellant (P), and an overall IRT observation.

The safety issues involved with the operations of the test facility were not considered by the IRT.

### 6.1 Requirements Observations and Recommendations

#### Observation R-1:

The Hot and Cold Soak tests defined in the PWR FRD are not adequate to verify the EDS restart, but provide limited data to be used in the EDS design process.


##### ***Recommendation R-1:***

***Reconsider this requirement to determine its benefit versus deferring testing until the EDS stage or simulated stage is available.***

#### Observation R-2:

Some facility requirements were defined to assess facility concepts/costs that could be used to assess engine design capabilities. This is consistent with prior programs. Historically, the development of a set of requirements for an altitude simulation facility is an iterative process



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between the engine and vehicle test requirements and the practicality of furnishing a facility to meet those requirements. Facility issues are generally the technical risks of the chosen concepts and the cost and schedule implications of the facility modifications. The current FRD appears to have been based solely on the engine test requirements.

### **Observation R-3:**

A feasibility study is an essential part of the process of evaluation/reassessment of program requirements. The usual approach is to (a) set a baseline; (b) make the necessary assumptions about requirements; (c) perform a preliminary design; and (d) reassess the requirements. This process is repeated until there is a solution that has an acceptable probability of satisfactory completion. At each cycle conclusion, important issues are defined and fed into the next cycle.


This B-2 feasibility study was accomplished with a reliable team approach, with technical studies by Jacobs Sverdrup Engineering, and with GRC/PBS being the primary support. The Jacobs Sverdrup Engineering support was in the May-September 2006 time frame. The GRC studies have continued in parallel paths for some concepts. The GRC personnel have presented some improvements to their center body diffuser (CBD) design which ameliorates some of the integration issues by shortening the diffuser from about 84 feet to about 54 feet. This allows additional space between the diffuser and flow deflector, and increases the water level to accommodate the inlet pressure needed for the dewatering pumps.

There appears to be adequate data to support evaluation/reassessment of program requirements using the feasibility study from PTIG and independent GRC studies.

### **Observation R- 4**

The driving facility parameters from sizing and risk viewpoints for altitude simulation for engine development, verification, and certification are: Altitude Operating Range (FRD 5.6) concurrent with the Steam Blocker (FRD 5.2), Thrust Level, Gimbal (FRD 5.4) and Nozzle Exit Diameter. Run Duration (FRD 5.1) is primarily a cost-driver since it defines the facilities to provide consumables i.e., propellants, steam, cooling water, etc.

The facility requirements for flow blocker and J-2X testing at maximum gimbal angles combine to require a diffuser design that is difficult to integrate into the existing PBS facility. Diffuser designs are typically Length/Diameter (L/D) correlations, resulting in pressure ratios at start and unstart operating conditions. The approximations for pressure in the spray chamber are dependent on the thermodynamic performance of the diffuser exhaust cooling and steam condensation in the spray chamber, as well as steam ejector design for the exhaust removal from the spray chamber and the potential flow restriction of the 12-foot spray chamber outlet. When operating periods of 550 seconds are specified, the net result is an excessive set of requirements.

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## 6.2 Integration Observations and Recommendations

### Observation I-1:

The modifications of the PBS B-2 facility to verify/certify the EDS thermal/vacuum capabilities and the J-2X restart for EDS are not defined. The PBS B-2 facility has been used to conduct Thermal/Vacuum Environmental Tests for restart of multiple burn space vehicles. However, modifications to satisfy the nozzle extension and engine performance requirements are likely to compromise the ability to perform the EDS required testing.

#### *Recommendation I-1a:*

*FRD for stage testing of restart capability should be initially based on historical data (S-IVB, Centaur, Delta III/Delta IV, etc.). EDS and J-2X element offices should evaluate the impact of the nozzle extension on EDS restart. The nozzle extension may not be required. There is precedence for this with Delta III/Delta IV.*

#### *Recommendation I-1b:*

*Restart tests should not be conducted without flight vehicle feedline simulation. This requires a vehicle or simulated vehicle in the test cell, and probably requires a test cell wall spool piece to provide adequate height for a test article.*

### Observation I-2:


The physical limitations of the PBS B-2 facility combined with the full set of requirements force unique design solutions. Considered individually, these unique solutions are attainable, but the combined solution may not be attainable; CBD is a prime example. Others include:

- 400,000 gallons/minute water for 10 minutes = 4,000,000 gallons or over 500,000 cubic feet.
- Engine combustion products flow rate is an order of magnitude greater than B-2 historical testing.
- Spray chamber volume is approximately 1/4 the volume of the spray chamber used for the prior testing of the J-2 engine. J-2X mass of flow rates are about 30% greater than those for J-2.
- B-2 original design was for 100k thrust engines.

## 6.3 Test Cell Observations and Recommendations

### Observation TC-1:

Access for engine hardware inspection and/or maintenance/repair downstream of the main

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chamber is not identified in the FRD. Access concepts will impact test chamber and/or diffuser and test turnaround schedules. Short, cooled clamshell diffuser section at diffuser inlet for an engine with nozzle extension does not permit adequate access for technicians and equipment for engine maintenance/inspection, including installation of the throat plug. Access via the long clamshell diffuser for testing without nozzle extension is adequate. Common access for all tests is highly desirable.

Engine injectors and nozzles require access for post-firing inspections. Therefore, a method to move or remove the diffuser section below the engine is needed. A potential concept is to provide a diffuser entrance section with a split clamshell to accommodate access. The design is complicated by the need for an active cooling system and the need for equipment to be moved in and out of the clamshell. There will probably be two different entrance section diffusers to accommodate tests with and without the nozzle extension.

Access platforms will also be required for maintenance, pre-test leak checks of the powerhead area, turbomachinery, instrumentation health monitoring, and other miscellaneous work. Local storage or removal of access platforms during tests is not defined.

***Recommendation TC-1:***

***Define facility concepts to provide access and assess impacts on other subsystems. A vertical access requirement is needed. Use 6 feet between the nozzle exit and the floor until the FRD requirement is added. Options should include raising the TTOS.***

**Observation TC-2:**


Testing of the Ares V EDS requires a height increase for the test cell.

***Recommendation TC-2:***

***Conduct a cost/benefit trade study to determine the effectiveness of significantly increasing the height of the test chamber. Evaluate raising the TTOS to improve engine access and review whether increased height will allow use of a double throat diffuser.***

**Observation TC-3:**

Thrust measurement/flow measurement precision required to determine thrust/Isp (Specific Impulse) delta differences between sea level performance without nozzle extension and vacuum performance with nozzle extension will not be easily attained. Because of this, measurement may not provide significant improvement over predicted performance based on analytical extrapolation of sea level measurements.

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J-2X vacuum performance is analytically predicted to be 294,000 pounds of force (lbf)/448 seconds. The predicted thrust and ISP differences between sea level, (no nozzle extension) values and vacuum (nozzle extension) are approximately 14,000 lbf and 18.8 seconds. Historical performance correlation of high area ratio nozzles with flight test data (e.g. RL10B-2) has been within 0.6 percent. The overhead required to produce and maintain thrust and propellant flowrate accuracies within the required 0.5 percent may not be achieved within facility funding and schedule constraints and may not be maintainable within the engine test program funding and schedule constraints.

A simple root-sum-squares (RSS) analysis of the projected thrust and flowrate measurements result in a predicted Isp error of approximately 0.66 percent. The real objective is not to determine the performance delta, but to determine the error in the predicted performance delta based on analytical models.

***Recommendation TC-3a:***

***The requirement to measure thrust and Isp should be re-addressed to determine if the cost and operational implications of the accuracy requirements can be justified by the potential improvement in flight performance prediction. Improvement potential and flight performance predictions should be compared to using high accuracy chamber pressure measurements and redundant flow meters.***

***Recommendation TC-3b:***


***If a thrust measurement system is not required, an optional solution may be a TTOS design that accepts both the J-2X and the EDS with minimum facility impact.***

**Observation TC-4:**

Some requirements that impact design envelope or operation are not addressed (i.e., facility world purge, facility water deluge). A facility world purge may be needed in the event of a major component rupture to minimize the accumulation of combustibles while other actions remove the source of leakage

A water deluge is the only practical way to contain a liquid oxygen (LOX) fire from a pump explosion. Such events in facilities that did not do all the maintenance and readiness preparations have resulted in serious facility damage.

These facility systems could be used to work operational problems with leakages of various sizes, so a wide range of operational impacts must be addressed, including head room for maintenance personnel.

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***Recommendation TC-4:***

***Evaluate world purge impact on spray chamber/ejector system operation due to increased non-condensable gas flow. Evaluate impacts of layouts on accessibility for maintenance operations.***

## 6.4 Spray Chamber Observations and Recommendations


### Observation SC-1:

The capability of achieving an acceptable rate of exhaust steam condensation in the spray chamber is judged to be the key risk consideration relative to acceptable spray chamber pressure. B-2 Trade Study Risk Mitigation is to continue evaluation via CFD and other simulation capabilities, methodology for anchoring predictions with actual test data, and subscale testing to support investigation of a steam cooling processes. There is, however, limited physical changes that can be made to the PBS spray chamber to improve its performance for J-2X testing.

The majority of steam from the J-2X engine and the flow blocker must be condensed for adequate performance. Experimental data to assess spray condensation is sparse and its application to B-2 is questionable. The Jacobs Sverdrup Engineering personnel indicated that the Arnold Engineering Development Center (AEDC) J-4 analysis was applied to B-2 without any changes to account for the decreased volume. CFD analyses have not been developed and/or validated to predict the condensation process in the presence of a non-condensable gas. Turbulence and coolant droplet size are significant factors, but probably quantitatively indeterminate. The volume for steam condensation is decreased as the water level is increased. It is probable that the steam condensation efficiency of the spray chamber will be influenced by the interaction of subsystems. It is unlikely that the interaction of the subsystems can be established prior to the facility activation.

***Recommendation SC-1:***

- ***If the studies and modeling do not yield a high level of confidence that the spray chamber pressure can be held low enough to maintain the diffuser operation, then an evaluation needs to be made to determine the utility of adding an additional spray chamber before the main ejectors.***
- ***A review needs to be made to ensure that the 12-foot diameter outlet is not a significant restriction.***
- ***As a subscale test is defined, considerations should include non-condensable hydrogen (H<sub>2</sub>) and scaling as a pie segment of the B-2 spray chamber.***

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- *The J-2X element planning should evaluate options to maintain the program schedule if the spray chamber pressure exceeds design value or modification to the spray chamber is required during activation to meet design value.*

#### **Observation SC-2:**

A CBD is required as a consequence of the depth of the B-2 spray chamber. Significant design challenges for CBD involve scalability, thermal environments, materials, and structural integrity. Subscale testing recommended in the trade study included cold flow and hot fire tests.

Inspection and maintenance of the installed configuration will be difficult, or impossible, so the thermal design needs to be conservative. However, existing design tools and processes should be adequate.

#### ***Recommendation SC-2:***

***Cold flow should provide an adequate basis for understanding diffuser operating characteristics.***

#### **Observation SC-3:**

The survivability of the propellant dump tanks located in the spray chamber is questionable. The dump tanks inside the test cell results in unnecessary risks due to the potential leakage of oxygen (O<sub>2</sub>) and/or H<sub>2</sub> into the spray chamber.

The survivability of the dump tanks can be assessed by engineering analysis. However, the tanks are an unnecessary complication relative to the de-watering of the chamber. They may impact the location of the structural support of the flow deflector. Removal of the tanks is the appropriate risk mitigation.

Current plans are to use the dump tanks to capture the propellants utilized in prestart engine conditioning (engine bleeds).


#### ***Recommendation SC-3:***

***Remove the dump tanks from the test cell. Route the engine conditioning propellants to disposal systems external to the test cell.***

#### **Observation SC-4:**

The flow deflector may be damaged by stagnation heating from the J-2X rocket exhaust.



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The flow deflector below the CBD was taken from J-4 test cell experience that includes J-2 engine testing. J-4 experience may not be conservative for B-2. The J-2X rocket exhaust flow is higher than J-2 and the flow deflector in B-2 is closer to the diffuser exit.

***Recommendation SC-4:***

***Cooling water to flow deflector should be provided using an approach consistent with other rocket engine test facilities.***

**Observation SC-5:**

The flow deflector below the CBD was taken from the J-4 test cell experiment as a means to keep the exhaust from blowing all the water out of the chamber. However, the previous B-2 testing was done with plume impingement into the water. The flow deflector may change the spray-chamber thermodynamics even though significant water from the spray chamber may reside above the flow deflector.

**Observation SC-6:**

The dewater pump system is a necessary item in the feasibility study. Discussions with PBS indicate that new pumps are required. The water level in the spray chamber needs to be minimized consistent with maintaining adequate head pressure to the pumps. Relocation of the pumps below their current level may be desirable.

## **6.5 Ejector System Observations and Recommendations**


**Observation ES-1:**

The steam generation system is a chemical generation system for the main ejectors and steam accumulators for the steam blocker.

- Accumulators are more expensive for the quantity of steam required for J-2X testing.
- Chemical generators increase the amount of non-condensable products in the spray chamber, which would result in increased spray-chamber pressure.
- Chemical generators impact recurring costs because of the increase in crew size necessary to operate and maintain the generators.

***Recommendation ES-1:***

***Conduct a cost-benefit study comparing the recurring and nonrecurring costs for both methods of steam generation for the main ejectors to ensure the most cost-effective selection is made.***

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## 6.6 Propellant System Observations and Recommendations

### Observation P-1:

Adequate propellant feed system similarity to a flight vehicle and/or the engine sea level ground test facilities cannot be achieved with single tank concepts for storage and run propellants.

Facility Constraints:

- Chamber provides 34-feet internal diameter x 54-feet high.
- Propellant run tanks are external to B-2 building.

Other Constraints:

- Flowmeter calibrations are location- and orientation-sensitive, so close similarity to the calibration installation is necessary to maintain calibration precision.
- Feed system design must limit line losses to keep propellant conditions within the engine start and mainstage limits.

### *Recommendation P-1:*

***Similarity to flight vehicle propellant feed system (or to the SSC sea level test facility) is necessary to preclude introduction of issues (e.g. engine start transient anomalies) that are unique to the test facility.***

### Observation P-2:


The propellant feed system concept results in several potential significant operating issues. The industry experience is that long propellant feedlines present major problems. The more remote the propellant tanks, the more difficult it is to control mixture ratio during start transients.

The liquid hydrogen (LH<sub>2</sub>) and LOX propellant storage are the run tanks; both are dewars located outside the test building. The propellant feed systems are not specified to have any similarity to either the vehicles or SSC test facilities. Current estimate of the LH<sub>2</sub> feedline length is in excess of 200 feet. The LOX feedline length was not estimated, but will be comparable.

Adequate propellant feedline similarity to a flight vehicle and/or the engine sea level ground test facilities cannot be achieved. CLV upper stage LOX feedlines may be less than 10 feet and sea level development feedlines in the 10's of feet. EDS LOX feedlines are expected to be comparable in length to the CLV Upper Stage.

Long horizontal run feedlines can result in unwanted thermal transients during engine operation.



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Line losses can prevent the system from providing pressure within the J-2X start limits and within the mainstage limits.

Flowmeter installation will require keeping the same upstream/downstream configurations as well as orientation to maintain the SSC-generated flowmeter constants.

Pressurization of a combined LOX storage/run tank with gaseous nitrogen (GN<sub>2</sub>) can lead to serious problems with nitrogen dilution.

***Recommendation P-2:***

***Relocate the run tanks into or close to the test cell. See Recommendation P-1.***

**Observation P-3:**

The J-2X run duration requirements may preclude the use of large internally located propellant run tanks.


Test durations greater than 100 seconds force the use of propellant tanks external to the test cell. This results in a feed system configuration that does not provide adequate simulation of the EDS. Additionally, design constraints on installation of the 12-inch LOX and LH<sub>2</sub> flowmeters to maintain an accuracy of 0.5 percent requires similar installation as the calibration facility. This further complicates this feed system configuration.

***Recommendation P-3:***

***Consider propellant system solutions such as intermediate duration tanks, O<sub>2</sub> tank internal to the test cell, the H<sub>2</sub> tank external close coupled to the test chamber (inside building) and utilize in-run propellant transfer similar to the procedure used at SSC.***


## **6.7 General IRT Observation**

Facility Refurbishment - The current test control and data center is 1960's vintage, and complete replacement of controls and data systems is planned with design criteria from SSC. Numerous other items are planned to be refurbished or replaced, and the list appears to be comprehensive. The concepts defined for the increase facility capability for J-2X are costly extensions of the current capability. The cost estimates for rehabilitation and increased capability were in the \$173-198M range. The cost estimates do not include all items and some of the cost-driving requirements are likely to be reduced. The IRT makes no judgment relative to these costs. Improved cost estimates will be obtained from the Architectural and Engineering (A&E) contractor.

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## 7.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the A/I/C that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment/inspection.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	An action identified by the assessment team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

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## 8.0 Acronyms List

A&E	Architectural and Engineering
AEDC	Arnold Engineering Development Center
ASE	Aero Systems Engineering
CBD	Center Body Diffuser
CFD	Computational Fluid Dynamics
CLV	Crew Launch Vehicle
CxP	Constellation Program
EDS	Earth Departure Stage
FRD	Facility Requirements Document
GN <sub>2</sub>	Gaseous nitrogen
GRC	Glenn Research Center
H <sub>2</sub>	Hydrogen
IRT	Independent Review Team
Isp	Specific Impulse
JSC	Johnson Space Center
L/D	Length/Diameter
lbf	Pounds of Force
LH <sub>2</sub>	Liquid Hydrogen
LOX	Liquid Oxygen
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
O <sub>2</sub>	Oxygen
PBS	Plum Brook Station
psia	Pounds Per Square Inch Absolute
PTIG	Propulsion Test Integration Group
PWR	Pratt & Whitney Rocketdyne
RPT	Rocket Propulsion Test
RPTMB	Rocket Propulsion Test Management Board
RSS	Root-Sum-Squares
S&MA	Safety and Mission Assurance
SSC	Stennis Space Center
TIM	Technical interchange meeting
TTOS	Thrust Takeout Structure

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## 9.0 References

- ASE, "Characterization of B-2 Operating Envelope", TR0029, dated 02-01-06
- Facility Design Trade Study to Conduct J-2X Thermal vacuum Testing at the Glenn Research Center Plum Brook Station B-2 Facility Final Report draft*, dated 12-19-06
- GRC, Presentation Material, "B-2 Analysis Efforts", dated 10-27-06
- GRC, Presentation Material, "B-2 Spray Chamber Modeling Efforts, Briefing to NESC Review Team", dated 12-21-06
- GRC, Presentation Material, "Briefing to Independent MSFC Engineering-led Study on J-2X Test Infrastructure", dated 12-05-06
- GRC, Presentation Material, "GRC PBS Facility Study Findings, Presentation to NESC", dated 11-08-06
- GRC, Presentation Material, "J-2 Engine Testing at B-2 Facility, GRC's Plum Brook Station", dated 10-26-06
- GRC, Presentation Material, "Status of B-2 Facility Exhaust Systems for J-2X", dated 11-08-06
- GRC, Presentation Material, "Status on B-2 Facility Rehabilitation and Modification Project", dated 08-09-06
- Jacobs Sverdrup Engineering, "Final Report Documenting the Results of the B-2 Test Cell Spray Chamber Study" dated 10-06
- Jacobs Sverdrup Engineering, Presentation Material, "B2 Test Cell Spray Chamber Study Presentation", dated 08-06
- PWR, "Facility Requirements Document, J-2X Upper Stage Engine for Altitude Testing", Draft., EID-XXXXXX, dated 11-10-06
- PWR, "Propulsion System Development Plan", RD06-154, dated 10-02-06
- PWR, Presentation Material, "J-2X System Test Requirements Status", dated 12-06-06
- SSC-PTIG, "Facility Design Trade Study to Conduct J-2X Thermal Vacuum Testing at the Glenn Research Center Plum Brook Station B-2 Facility Final Report" Preliminary Draft, dated 11-17-06
- SSC-PTIG, "Facility Design Trade Study to Conduct J-2X Thermal Vacuum Testing at the
- SSC-PTIG, Presentation Material, "Facility Design Trade Study to Conduct J-2X Thermal Vacuum/Hot-Fire Engine Testing at Plum Brook Station, Preliminary Report Results Briefing @PBS", dated 08-15-06
- SSC-PTIG, Presentation Material, "GRC PBS Facility Study Findings Presentation to Glen


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Doughty", dated 10-12-06


SSC-PTIG, Presentation Material, "GRC PBS Facility Study Findings Presentation to NESC",  
dated 11-08-06

## **Volume II: Appendices**

A. NESC Request Form (NESC-FM-03-002)


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## Appendix A. NESC Request Form

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NASA Engineering and Safety Center Request Form		
Submit this ITA/I Request, with associated artifacts attached, to: <a href="mailto:nrbexecsec@nasa.gov">nrbexecsec@nasa.gov</a> , or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681		
<b>Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt</b>		
Received (mm/dd/yyyy h:mm am/pm) 8/3/2006 12:00 AM	Status: New	Reference #: 06-049-E
Initiator Name: Kevin P. Power	E-mail: <a href="mailto:kevin.p.power@nasa.gov">kevin.p.power@nasa.gov</a>	Center: SSC
Phone: (228)-688-1490, Ext _____	Mail Stop: PA11	
Short Title: Feasibility of Conducting J-2X Engine Testing at the GRC Plum Brook Station B-2 Facility		
Description: BACKGROUND: The J-2X Assembly, Integration, and Test (AIT) office located in the Exploration Launch Office (ELO) at MSFC requested that a study be completed examining the capability and feasibility of the GRC Plum Brook Station (PBS) B-2 Facility to conduct J-2X engine testing in thermal vacuum conditions. Subsequent testing of the J-2X engine mated with the Earth Departure Stage was also to be examined. Deliverables of the study included the following: - Design Concept (pre-Phase A) - Acquisition Strategy - Propulsion Test Operations Work Plan - Life Cycle Cost Estimate - Life Cycle Schedule Estimate To conduct the study an independent multi-center study team was convened and headed by the SSC Propulsion Test Integration Group (PTIG), which operates as an agent for the Level 2 CxP Test & Verification (T&V) Office and supports the Level 3 T&V offices with rocket propulsion test formulation and planning. The study team focused its technical efforts on examining the integrated interaction of the spray chamber exhaust diffuser, steam injector, cooling water, and steam ejection sub-systems utilized for maintaining the altitude test condition requirements. Other technical analysis examined the capability of the vacuum chamber, thrust measurement system, thrust take-out structure, and propellant run systems in meeting the thermal vacuum test condition requirements. Preliminary results will be available the week of 22 Aug 2006 with the final results planned for release prior to 15 Sep 2006.		
REQUEST: The PTIG, as an agent for CxP T&V, is requesting an NESC-led independent assessment (i.e. peer review) of the study results prior to final release..		
Source (e.g. email, phone call, posted on web): e-mail		
Type of Request: Independent Assessment requested		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
<b>Section 2: Systems Engineering Office Screening</b>		
<b>Section 2.1 Potential ITA/I Identification</b>		



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Received by SEO: (mm/dd/yyyy h:mm am/pm): 8/3/2006 12:00 AM	
Potential ITA/I candidate? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No	
Assigned Initial Evaluator (IE): Shamim Rahman	
Date assigned (mm/dd/yyyy): 8/6/2006	
Due date for ITA/I Screening (mm/dd/yyyy):	
<b>Section 2.2 Non-ITA/I Action</b>	
Requires additional NESC action (non-ITA/I)? <input type="checkbox"/> Yes <input type="checkbox"/> No	
If yes:	
Description of action:	
Actionee:	
Is follow-up required? <input type="checkbox"/> Yes <input type="checkbox"/> No If yes: Due Date:	
Follow-up status/date:	
If no:	
NESC Director Concurrence (signature):	
Request closure date:	
<b>Section 3: Initial Evaluation</b>	
Received by IE: (mm/dd/yyyy h:mm am/pm):	
Screening complete date:	
Valid ITA/I candidate? <input type="checkbox"/> Yes <input type="checkbox"/> No	
Initial Evaluation Report #: NESC-PN-	
Target NRB Review Date:	
<b>Section 4: NRB Review and Disposition of NCE Response Report</b>	
ITA/I Approved: <input type="checkbox"/> Yes <input type="checkbox"/> No	Date Approved: Priority: - Select -
ITA/I Lead: , Phone ( ) - , x	
<b>Section 5: ITA/I Lead Planning, Conduct, and Reporting</b>	
Plan Development Start Date:	
ITA/I Plan # NESC-PL-	
Plan Approval Date:	
ITA/I Start Date	Planned: Actual:
ITA/I Completed Date:	
ITA/I Final Report #: NESC-PN-	
ITA/I Briefing Package #: NESC-PN-	
Follow-up Required? <input type="checkbox"/> Yes <input type="checkbox"/> No	
<b>Section 6: Follow-up</b>	
Date Findings Briefed to Customer:	
Follow-up Accepted: <input type="checkbox"/> Yes <input type="checkbox"/> No	
Follow-up Completed Date:	
Follow-up Report #: NESC-RP-	
<b>Section 7: Disposition and Notification</b>	
Notification type: - Select -	Details:
Date of Notification:	
Final Disposition: - Select -	
Rationale for Disposition:	
Close Out Review Date:	



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### Form Approval and Document Revision History

Approved: _____ NESC Director	_____ Date
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Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p><b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b></p>					
1. REPORT DATE (DD-MM-YYYY) 01-01-2008		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To) Aug 2006- Mar 2007	
4. TITLE AND SUBTITLE  Feasibility of Conducting J-2X Engine Testing at the Glenn Research Center Plum Brook Station B-2 Facility				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)  Schafer, Charles, F.; Cheston, Derrick, J.; Worlund, Armis L.; Brown, James R.; Hooper, William G.; Monk, Jan C.; Winstead, Thomas W.				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER  510505.01.07.01.06	
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12. DISTRIBUTION/AVAILABILITY STATEMENT  Unclassified - Unlimited Subject Category 20 Spacecraft Propulsion And Power					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT  A trade study of the feasibility of conducting J-2X testing in the Glenn Research Center (GRC) Plum Brook Station (PBS) B-2 facility was initiated in May 2006 with results available in October 2006. The Propulsion Test Integration Group (PTIG) led the study with support from Marshall Space Flight Center (MSFC) and Jacobs Sverdrup Engineering. The primary focus of the trade study was on facility design concepts and their capability to satisfy the J-2X altitude simulation test requirements. The propulsion systems tested in the B-2 facility were in the 30,000-pound (30K) thrust class. The J-2X thrust is approximately 10 times larger. Therefore, concepts significantly different from the current configuration are necessary for the diffuser, spray chamber subsystems, and cooling water. Steam exhaust condensation in the spray chamber is judged to be the key risk consideration relative to acceptable spray chamber pressure. Further assessment via computational fluid dynamics (CFD) and other simulation capabilities (e.g. methodology for anchoring predictions with actual test data and subscale testing to support investigation.					
15. SUBJECT TERMS  Computational fluid Dynamics (CFD), Propulsion Test Integration Group (PTIG), J-2X, Diffuser, Propulsion, spray chamber subsystems, Earth Departure Stage (EDS), Thrust Takeout Structure (TTOS), Plum Brook Station, root-sum-squares (RSS)					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
UU	UU	UU	UU	34	19b. TELEPHONE NUMBER (Include area code) (301) 621-0390